DESIGNING TRANSPORTABLE COLLECTIVELY PROTECTIVE SHELTERS FOR THERMAL EFFICIENCY

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ABSTRACT

This paper discusses different techniques for designing a transportable collectively protected shelter that is thermally efficient, meaning that the heating and cooling capacity needed to maintain a comfortable environment is minimized.

For transportable collectively protected shelters, two areas of shelter design can be optimized to produce a shelter that is thermally efficient. First, a radiant barrier coating can be applied to either the shelter surface or a liner, or a solar shade can be used to reduce the radiant heat load. Secondly, the shelter and chemical/biological (CB) liner need to maintain membrane separation to increase the thermal resistance of the system by creating a dead air space.

INTRODUCTION

This paper on thermal effects inside of transportable collectively protected shelters (TCPS) focuses on four transportable military shelters: the Medical Small Shelter System (Medical SSS), the Tent Extendable Modular Personnel (TEMPER), the Modular General Purpose Tent System (MGPTS), and the Medium Shelter System (MSS). The Medical SSS is used in the Collectively Protected Expeditionary Medical Support (CP EMEDS), the collectively protected TEMPER is used in the Chemically Hardened Air Transportable Hospital (CHATH) and Collectively Protected Deployable Medical Shelter (CP DEPMEDS), a liner system is currently under development for the MSS, and the Interim Collective Protection System (ICPS) is the collectively protected version of the MGPTS. The purpose of this paper is to assess the thermal attributes of existing TCPS, with the goal of providing recommendations that can be employed in the design of an entirely new TCPS such as the Joint Transportable Collective Protection System (JTCOPS), or can be applied to improve the efficiency of the current generation of collectively protected shelters.

Previous work on the thermal effects inside of fabric structures that was used as background material for this study include:

- Hot weather performance testing of CP EMEDS system done by AAC/WMO (Dec. 2000)[i]
- Thermal testing as part of a test regimen for ICPS done by AAC/WMO (Nov. 2001)[ii]
- Thermal effects inside of tensioned fabric structures, PhD thesis by Dr. Gregor Harvie[iii]

The threat of a chemical/biological attack is greatest in hot environments making these areas the most apt to need a collectively protected shelter. This paper focuses on methods to maintain the effects of cooled air from any air conditioner for as long as possible in a hot environment. Using the recommendations presented here, a collectively protected shelter will require less cooling and heating and be more comfortable than one that does not incorporate these recommendations.

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OVERVIEW OF THERMAL THEORY

Conduction

Thermal conduction occurs when two substances are in thermal contact and there is a thermal imbalance between them (they are at different temperatures). The thermal energy transferred due to conduction is represented by the following formula:

$$Q = -kA \cdot \Delta t \cdot \frac{dT}{dx}$$

where Q is the energy transferred in Joules, k is a constant for the thermal conductivity of the material, A is the area, Δt is the time in seconds, and dT/dx is the temperature gradient between the two surfaces. Table 1 below gives the thermal conductivities, k, for some sample substances. Please note that as the k values decrease, the substance becomes a better insulator against heat.

TABLE 1. Thermal Conductivities of Sample Substances

Substance	Thermal Conductivity
	W/m•°C
Copper	390
Aluminum	238
Iron	79.5
Stainless Steel	32.9
Concrete	0.8
PVC	0.17
Wood	0.14
Fiberglass	0.038
Still Air	0.023
Silica Aerogel	0.020

Convection

Convection occurs when the movement of a heated substance (usually air) transfers thermal energy. When this movement is caused by differences in density, it is called natural convection; when the movement is caused by a fan or pump, it is called forced convection. The most basic formula for convection is:

$$Q = hA \cdot \Delta T$$

where Q is the energy transferred in Joules, h is the convection heat-transfer coefficient, A is the area and ΔT is the difference in temperature. The h value actually represents a series of significantly more complex formulas, which include such factors as wind speed across the surface, and properties of the surface material. Explaining the complexities of convective heat transfer is beyond the scope of this document; so only the above equation is presented.

Radiation

Whereas conduction and convection require a medium to transfer thermal energy, radiation does not. All objects radiate energy continuously in the form of electromagnetic waves, and the rate of energy transfer between two objects is proportional to the area of the two objects, the temperature difference between them and emissivity of the radiating object and the reflectivity of the receiving object. This is represented by the following formula:

$$P = \sigma A e T^4$$

where P is the power radiated in Watts, σ is a constant equal to 55.6696x10^{-8} W/m^2K^4, A is the surface area in m^2, e is the object's emissivity, and T is the temperature in Kelvin. The emissivity, e, is a value between 0 and 1 and represents the substance's ability to absorb and emit radiation. The emissivity is related to the reflectivity in that for opaque substances, the reflectivity and the emissivity must add up to 1. For example, aluminum is a poor emitter but a good reflector; since it has an emissivity of about 0.1, it

must have a reflectivity of approximately 0.9. Table 2 gives the emissivities and reflectivities of some selected substances.

The emissivity of a substance is not constant for all wavelengths of radiation. For example, a surface painted white and a surface painted black have nearly the same emissivity and both look black in the far infrared spectrum; the white surface only has a high reflectivity in the visible light spectrum. However, a black object gets hotter than a white object when it is placed in sunlight because sunlight has the greatest intensity in the visible light spectrum; the white object reflects this radiation while the black object absorbs it. This absorbed energy is converted to thermal energy that, as the object gets hotter, is radiated in the far infrared spectrum. See Figure 1 below for a graph of solar intensity versus radiation wavelength.

TABLE 2. Reflectivity and Emissivity of Selected Substances

Substance	Reflectivity	Emissivity
Aluminum, polished	0.90 to 0.95	0.10 to 0.05
Aluminum, oxidized	0.70 to 0.80	0.30 to 0.20
Steel, polished	0.45	0.55
Steel, oxidized	0.15	0.85
Painted surface, white	0.08 to 0.15	0.92 to 0.85
Painted surface, black	0.10 to 0.18	0.90 to 0.82
Rubber	0.06	0.94
Water	0.05	0.95

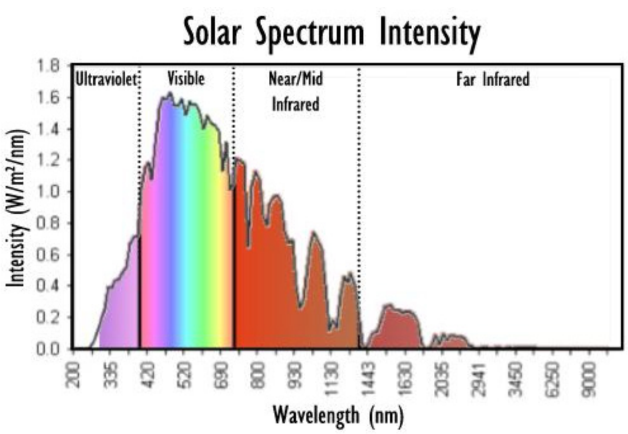

Figure 1. Solar Intensity Versus Wavelength Distribution.

HEAT TRANSFER IN TRANSPORTABLE COLLECTIVELY PROTECTED SHELTERS

Collectively protected shelters gain thermal energy from the following sources:

- **Radiation** – The sun is the largest source of radiant energy a shelter will be exposed to. A shelter can be exposed to 1150 W/m², or more, of radiant energy when the sun is at its zenith. Because of its high emissivity and low reflectivity, the shelter cladding will absorb approximately 90% of incident radiation. The radiation will cause the outer cladding temperature to rise and radiate heat to the outside and inside environment (the thermal liner or CB liner, whichever is the next layer) and will lose heat to any dead air space trapped between the cladding and the liner through convection. The shelter will also radiate to any large object that is in close proximity with the intensity being inversely proportional to the distance. For example, if a large ISO container is placed next to a shelter, the ISO container and the shelter will radiate energy to each other. They will both end up being hotter than if the two were placed further apart.

- **Ambient Environment** – Thermal energy is gained or lost through convection when the outside temperature is different from the shelter cladding temperature. In a hot environment, the movement of hot air against the shelter cladding transfers energy from the ambient air to the cladding, where it is then transferred to the shelter interior or dead air space by radiation, convection or conduction. This occurs in a boundary layer of air across the shelter whose thickness is determined by wind velocity, difference in temperature between the cladding and the ambient air, and the shape of the building. However, when the cladding gets hotter than the ambient air when the sun is intense, ambient convection actually cools the cladding.

- **Blower –** For a building of conventional construction, 20% to 50% of the heating and cooling load comes from the exchange of ambient and interior air, which includes infiltration, exfiltration and forced-air ventilation (25% is the rule-of-thumb used by HVAC engineers[iv]). However, for transportable collectively protected shelters, the CB liner eliminates all sources of air infiltration. By taking a measured quantity of ambient air, pushing it through a filter and pressurizing the interior of the CB liner, the filter/blower acts as the collectively protected equivalent of infiltration. From a thermal standpoint, this air is worse than regular infiltration because the air from the filter/blower is hotter than ambient air primarily due to friction of the blower blades against the air and heat generated by the electric motor. Testing has shown that an FFA-400[v] will induce on average an 11°F rise in temperature over ambient, and an M28 blower/HSFC will induce a 14°F rise in temperature over ambient[vi].

- **Ground –** The earth is the largest heat source/sink accessible for most buildings, hence the interest and developmental work in geothermal energy and heat pumps. However, in a transportable shelter, the thermal energy conducted through the ground reaches a steady state value in a few days, and is quite minor in magnitude when compared with other sources. Transportable collectively protected shelters typically have additional flooring to protect the CB liner, which further insulates the shelter interior from the ground. This reduces the effects of ground conduction to the point where it can be disregarded as a contributing thermal factor for shelter efficiency calculations.

- **Internal Load** – In a conventional building, heat from sources such as people, electronic devices and equipment can be anywhere from 3% to 40% of the total heat load, depending on the number of occupants and the devices present. In a transportable shelter, a good value for the internal load would be 23% for a heavily occupied shelter and 3% for an unoccupied shelter with no devices or appliances.[vii]

- **ECU** – The Environmental Control Unit (ECU), as the only sink for thermal energy, has to offset all of the other sources.

When a shelter is placed in a cold environment (the interior is heated), the same processes as above apply; only the direction of the heat flow is reversed. Figure 2 below illustrates the sources of thermal energy in a collectively protected shelter.

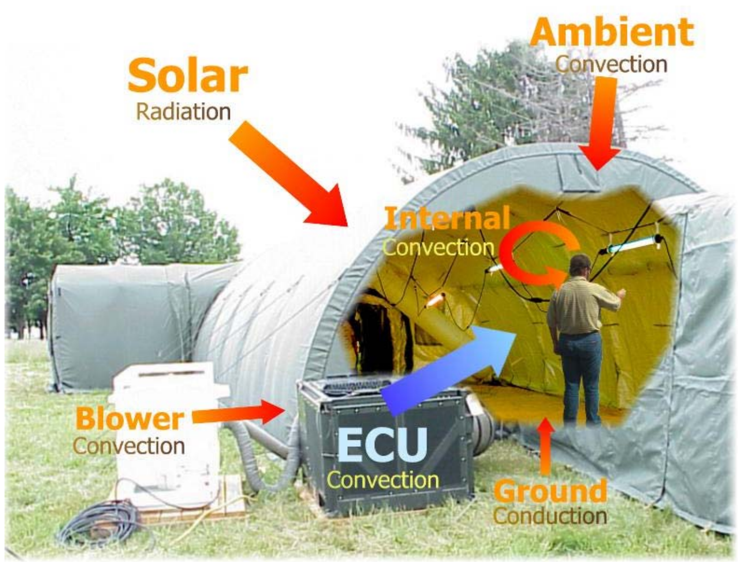

Figure 2. Heat Sources and Sinks in Collectively Protected Shelters.

MATERIALS

For a conventional building, the thermal efficiency can be increased by material selection. The use of different insulation, structural materials or surface treatments, can greatly increase the effective thermal resistance or R-value of the building. However, transportable shelters must use fabric surfaces because of mobility and setup considerations, and fabric provides almost no insulative value. Even if a new, space-age fabric was available that had a significantly lower thermal conductivity constant, this new fabric would produce almost no thermal difference over fabrics currently in use. The formula for thermal conduction, as stated above, is:

$$Q = -kA \cdot \Delta t \cdot \frac{dT}{dx}$$

The *dT/dx* differential is the temperature gradient across the thickness of the material, with the *dx* being the thickness component. Because shelter fabric is so thin (only 2 to 35 mils thick), the *dx* term is so small that it overwhelms a low thermal conductivity (*k*) value. Because of this, the bottom side of the fabric is the same temperature as the top and, for thermal calculations, one can assume instantaneous thermal conduction through the material.

Even though the choice of shelter materials cannot reduce the ambient convection load, they can reduce the radiant load on the shelter interior. The radiant load from the sun is significant and is the largest single thermal load on the shelter. A fabric structure responds almost instantly to solar loading because of its small thermal mass; the surface temperature has been observed to increase over 27°F in less than 1 minute[viii]. So if even a fraction of this solar energy can be reflected instead of absorbed, thermal efficiency could be significantly increased. Figure 3 illustrates the relative magnitude of radiation emitted inside a shelter to incident solar radiation for a shelter utilizing two layers of similar materials (such as TEMPER or MGPTS).

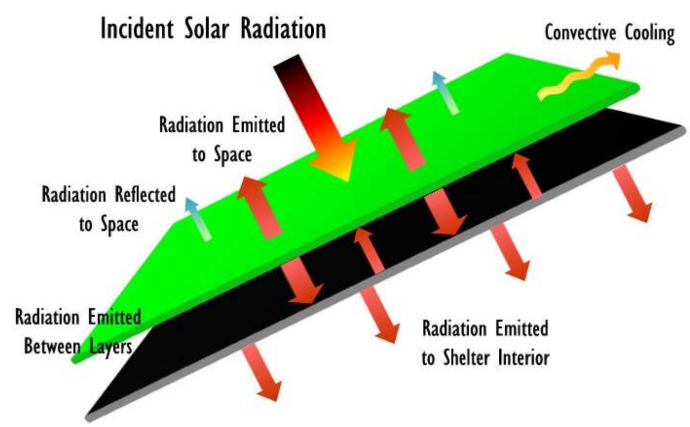

Figure 3. Radiant Energy Emitted Into Shelter Interior.

A solar shade (used to keep the top of the shelter in the shade) is the most basic, but still effective, method of reducing solar load. When the solar shade absorbs radiation, it initially emits approximately half of the energy from each side. This decreases the radiant energy incident on the shelter cladding by 50% over a shelter having no solar shade. An added advantage is that, as the solar shade gets hotter, convective cooling occurs on both sides of the solar shade as opposed to an unshaded shelter where only the top side of the cladding is convectively cooled. Thus, the total solar radiation that is incident on the shelter cladding is reduced by 60 to 75% by installing a solar shade. Figure 4 illustrates the magnitude of energy emitted inside a shelter relative to incident radiation for a shelter with a solar shade (such as TEMPER with the solar fly installed).

Another method to reducing radiant load is to use a material that reflects radiant energy. Aluminum has a very high reflectivity (approximately 0.9), and is used as a radiant barrier material by the housing industry. A very thin layer of aluminum can be laminated onto fabric, which can then be used for

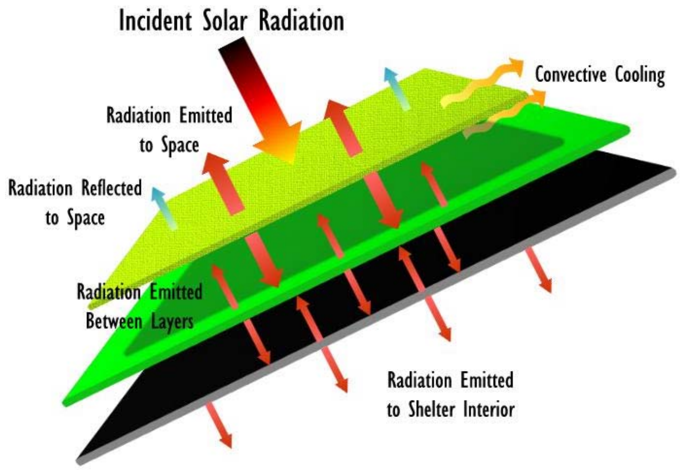

Figure 4. Effect of a Solar Shade Upon Radiant Energy Emitted Into Shelter Interior.

the cladding or the liner. Using this material for the cladding would be thermally effective, but the shelter would not be visually camouflaged, which is unacceptable. A more acceptable configuration is to use the aluminum laminate fabric for the liner. Because the reflected radiation is absorbed by the cladding and then emitted to the environment, this configuration is just as efficient as having a reflective cladding. Figure 5 illustrates the magnitude of energy emitted inside a shelter relative to incident radiation for a shelter with a reflective liner (such as the Medical SSS).

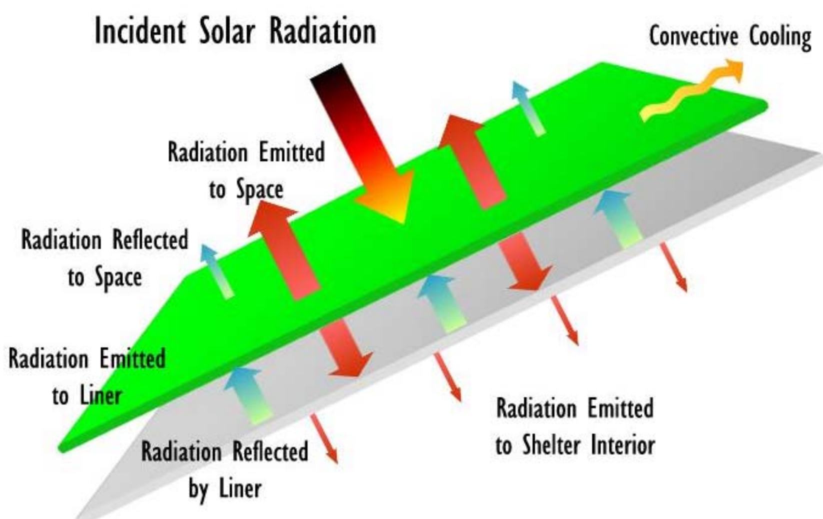

Figure 5. Effect of Reflective Liner Upon Radiant Energy Emitted Into Shelter Interior.

Currently, only the Medical SSS and the MSS uses a reflective liner, but any shelter could be retrofitted with one. Figure 6 shows a liner section from a TEMPER and Figure 7 shows a section of Medical SSS liner.

Figure 6. TEMPER Liner Section.

Figure 7. Medical SSS Liner Section.

Note that for both the TEMPER and Medical SSS, the side of the fabric that faces inside the shelter is white. But for the side that faces the shelter cladding, the TEMPER liner in black vinyl coated fabric while the Medical SSS liner in reflective aluminum.

Although a radiant barrier only allows around 5 to 10% of the incident radiant energy to be emitted into the shelter interior, this does not reduce the total heat load on the shelter by solar radiation by 90 to 95%. With a reflective liner installed, the cladding absorbs the reflected radiation. The cladding is consequently hotter than it would be with a normal fabric liner. Because emittance is a function of the temperature difference between the two surfaces, the cladding will emit more radiation to the liner. So despite the liner emitting only 5 to 10% of the radiation into the shelter, it is 5 to 10% of a greater radiation total compared to a nonreflective liner. The increased cladding temperature also increases the convective heat transfer rate to the inner liner, as this is also a function of temperature difference. Instead of a 90% reduction in the transfer of solar energy, only a 50 to 60%[ix] reduction is actually obtained. But a 50 to 60% reduction at noon solar intensity is a significant improvement.

SHELTER CONFIGURATION

While material selection can reduce the radiant load on the shelter's interior, the physical design of the shelter can also reduce the magnitude of ambient convective heat transfer. A shelter's thermal characteristics can be greatly improved by restraining the CB liner, providing multiple fabric layers, and/or by making the layers as leak-proof as possible.

CB Liner Restraint

When a shelter is collectively protected, a major source of thermal inefficiency is introduced into the system when the thermal liner is allowed to make direct contact with the shelter's liner or cladding. The multiple layers of fabric, when pressed together, act as if they were a single layer (as when the TEMPER has the M28 liner/CB liner installed). When the M28 liner is installed inside the TEMPER, the temperate liner is not installed. Even if it were, it would have no thermal impact because the M28 liner is designed to be slightly larger than the shelter interior, and when the liner is inflated, it presses up against the shelter cladding. See Figure 8 for a view of the interior of a collectively protected TEMPER. Note how the CB liner makes contact with the shelter fabric.

Figure 8. Interior of TEMPER with M28 Liner.

The magnitude of this problem was shown by testing conducted by AAC/WMO using a Medical SSS shelter in December of 2000[x]. For this test, a Medical SSS shelter was set up inside the main climatic chamber at the McKinley Climatic Laboratory, and was subjected to 118°F ambient temperature and variable solar loading that peaked at 1150W/m². The Medical SSS used a single FDECU[xi] for cooling and an FFA-400 for filtered air. Two different configurations were tested:

1. The CB liner was unrestrained, and when inflated it pressed the Medical SSS's thermal liner into the cladding, making the cladding/thermal liner/CB liner act as a single layer of fabric.
2. An improvised restraint system made out of construction fencing was installed to prevent the CB liner from making contact with the thermal liner.

Figure 9 below shows the shelter interior with the construction fencing installed as an improvised restraint system, and Figure 10 shows the average shelter interior temperatures under maximum solar load (1150 W/m²).

Figure 9. Medical SSS with Improvised Restraint System.

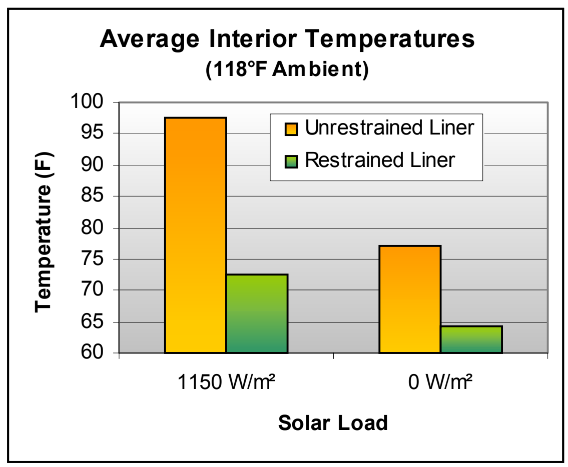

Figure 10. Average Interior Temperatures During Medical SSS Climatic Testing.

Note that the average interior temperature dropped from 98°F to 73°F for full solar loading when the liner restraint was installed. This clearly showed the magnitude of improvement in thermal efficiency by restraining the CB liner. Because of this testing, a CB liner restraint system was designed for the Medical SSS, and integrated into CP EMEDS system. Figure 11 shows the interior of a CP EMEDS shelter before the liner restraint was integrated, and Figure 12 shows a CP EMEDS shelter interior with a liner restraint system installed.

Figure 11. CP EMEDS with Unrestrained Liner.

Figure 12. CP EMEDS with Restrained Liner.

Any shelter that employs a pressurized CB liner system will benefit thermally from restraint of the liner. Some designs, however, partially or fully restrain the liner without a separate system. The ICPS (MGPTS with CB liner(s)) is thermally more efficient than the either the Medical SSS or the TEMPER with unrestrained CB liners. The ICPS uses one or two identical but separate CB liners designed to be smaller than the interior volume. The base of the liner is staked to the ground, which prevents the CB liner from becoming tubular in shape. The CB liner thus becomes self-restraining with significant airspace maintained between the top of the CB liner and the MGPTS liner. Figure 13 shows the interior of an MGPTS with a single CB liner installed; note the airspace above the CB liner. Figure 14 shows the interior of an ICPS liner; note how the natural tendency of a CB liner is to assume a spherical or tubular shape. The ICPS liner still makes contact with shelter sides and ends and is, therefore, not thermally optimalized. By restraining the ICPS liner to prevent it from making contact with the shelter walls, the thermal performance of this system would be improved.

Figure 13. ICPS Liner Inside MGPTS.

Figure 14. Interior of ICPS Liner.

The best possible method to preventing the CB liner from making contact with the shelter cladding and liner is to design the CB liner to be self-restraining. The program to collectively protect the MSS is using this approach to liner design and is currently producing a self-restraining prototype liner. Figure 15 shows a MSS, and Figure 16 shows the end view drawing of the prototype liner installed inside an MSS.

Figure 15. Medium Shelter System (MSS).

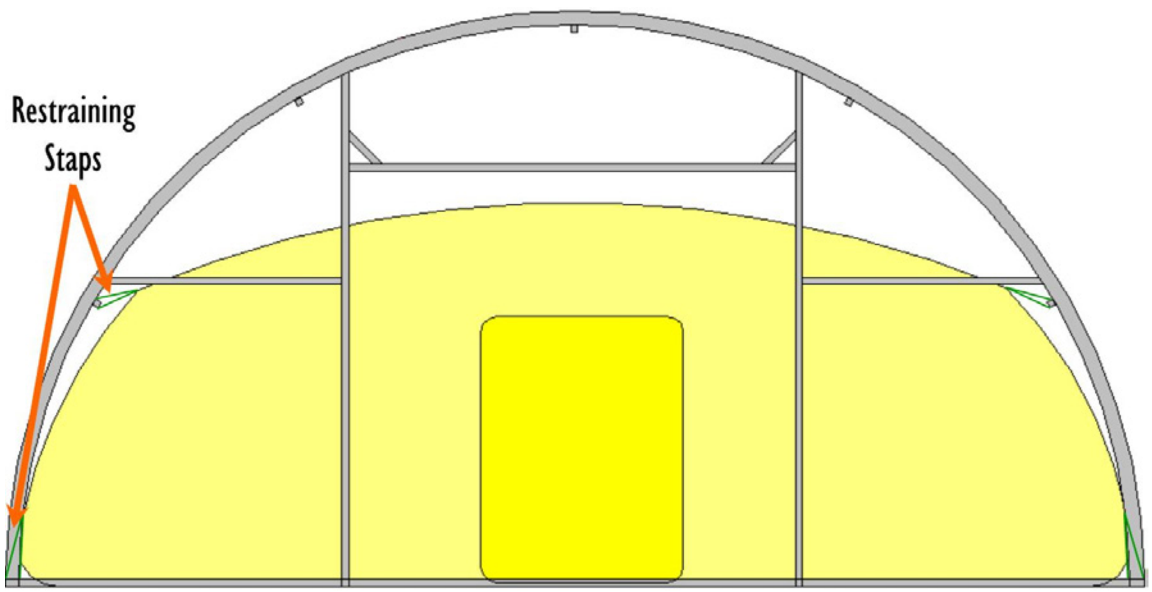

Figure 16. Drawing of Prototype Self-Restraining MSS Liner.

Note at how the force of the liner trying to become circular is transferred to the shelter framework by straps at the base and the shoulder purlins. The tension of the liner fabric between tie-off points keeps its form, which is designed to not touch the shelter liner.

Dead Air Space

A conventional building that is intended for human habitation is usually not made out of a single thin layer on top of a frame. Usually, a wooden frame is used as the base structure, a plywood layer with siding is used as the outer layer, and sheetrock and interior finish is used as the inner layer. The space between these two layers is filled with some form of insulation. But for transportable shelters,

conventional insulation such as fiberglass batts is two bulky; enough fiberglass to insulate a TEMPER, MGPTS or Medical SSS can more than double the bulk that needs to be shipped. Consequently, a type of insulation that does not increase bulk and weight is needed, and the best candidate for that is air.

Still air makes an effective insulator. A vertical air space that is 3½ inches wide provides an R-value of 1.01[xii] by itself. When this is added to the R-values for the fabric (0.02 x 2), the air film along the outside layer (0.25 for summer, 0.17 for winter) and the air film along the inside layer (0.92), we get an R-value of 1.01 + (0.02 x 2) + 0.25 + 0.92 = 2.22. A shelter constructed of a single membrane of fabric (no dead air space) has about half the R-value; 0.02 + 0.25 + 0.92 = 1.19.

During the Medical SSS CB liner restraint testing in the climatic chamber, the contribution of the thermal liner on the Medical SSS was tested. With the ambient temperature held at a constant 118°F, a Medical SSS that was cooled by an FDECU was tested for one day with the thermal liner installed (two membranes with a dead air space) and one day with the thermal liner removed (single membrane). Figure 17 shows the results of this test.

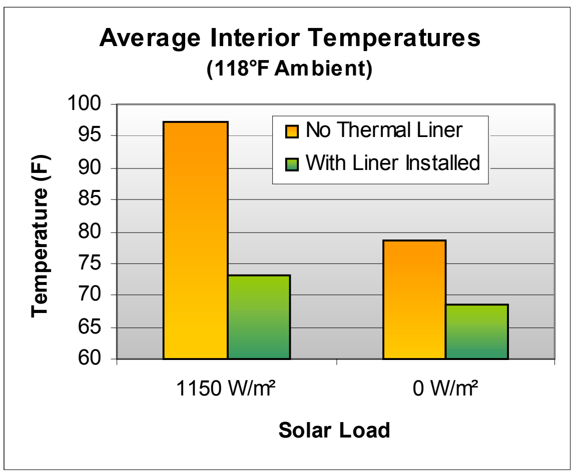

Figure 17. Effect of Shelter Liner on Medical SSS.

Note that the inclusion of a thermal liner, which is so thin that it has no insulative value, reduced the average interior temperature by 24°F under full solar load and by 10°F with no solar load. The dead air space between the layers of fabric became the shelter's insulation. It should also be noted that the dead air is significantly hotter than the air inside the shelter. It is therefore very important to prevent this hot air from leaking into the shelter. The liner therefore needs to be as airtight as possible.

Sealing the Liner

Because the air inside the dead air space must be as still as possible to provide the maximum insulative value, air movement within this space greatly reduces its effectiveness as a thermal barrier. As stated previously, when the shelter is air conditioned in a hot environment, the dead air is significantly warmer than the air inside the shelter and must not be allowed to leak into the shelter. All of the military transportable shelters currently used for collective protection do not effectively seal this airspace from the interior and/or exterior environment. The liner inside the TEMPER and inside the MGPTS hangs loose to the floor, and the liner inside the Medical SSS leaves a 2 to 3 inch gap from the bottom to the floor, as shown in Figure 18.

Figure 18. Gap at the Bottom of the Medical SSS Thermal Liner.

Although this has not been tested for the air conditioning case (cooling a shelter in a hot

environment), the thermal effect of sealing the liner to the floor was tested for cold environments. In January 2001 AAC/WMO conducted a shelter-heating test using various heaters with non-collectively protected shelters for a heater acquisition program. Using a single Hunter UH70 fuel-fired heater on the TEMPER and another one on the Medical SSS, the maximum interior temperature was recorded at -25°F ambient. The liners were then sealed to the floor using plastic sheeting and duct tape, and the interior temperatures were again recorded. Figure 19 shows the expedient sealing of the liner in the Medical SSS, and Figure 20 shows the test results.

Figure 19. Expedient Sealing of Medical SSS Liner Gap.

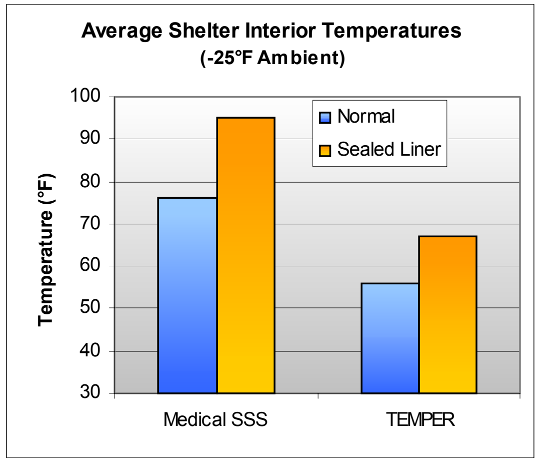

Figure 20. Average Interior Temperatures For Heating TEMPER and Medical SSS with UH70 Heater.

Sealing the liner to the floor increased the interior temperature by 19°F in the Medical SSS and by 11°F in the TEMPER. Because of the shelters' geometry, the impact from sealing the liner was greater than for the cooling case. When cooling, the hot air is pushed upwards through the dead air space by cooler air at the bottom, and it stays at head height or higher when it seeps in where it is less noticeable. The effect would also be less for a TCPS because the infiltrating air is prevented from entering the Toxic Free Area (TFA) by the CB liner. See Figure 21 for an illustration of this effect, and how it affects the shelter interior environment.

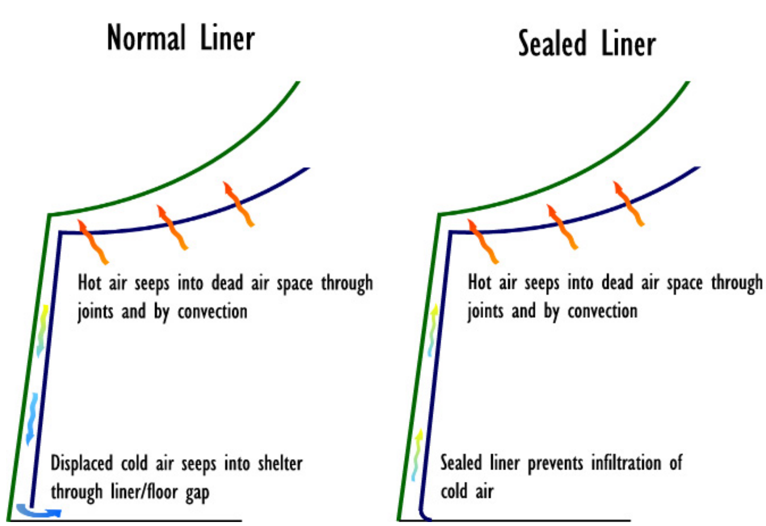

Figure 21. Effect of Sealing the Liner to the Floor During Cold Weather (Heating Case).

ADVANCED CONCEPTS

The largest area of heat transfer that has not been addressed by any transportable shelter is the convective currents that form inside of the dead air space. Air is a very effective insulator when it is not moving, but any time areas of air are at different temperatures, the warmer air is less dense and tends to rise while the colder air is denser and tends to sink. This is how convective currents are formed, which makes air a significantly less effective insulator.

Insulation such as fiberglass and foam are thermally resistant because they prevent air movement. Insulation is made up very small cells air encased by thin walled material that has a low thermal conductivity. This makes a very low-density solid, which is used to completely fill what would otherwise be empty space in the walls and ceiling of conventional buildings.

In order to limit the convective currents inside the dead air space, something other than conventional insulation is needed. One possibility, that adds minimal bulk and weight to the shelter, is to subdivide the dead air space using the same airtight, lightweight fabric used for the liner. These dividers would run horizontally along the full length of the shelter, and would be attached to the cladding and the liner. In effect, this changes the dead air space into insulation with very large air cells. There still will be fairly significant convective currents inside each cell, but the sum of these currents would be less than the large currents that form in open vertical spaces. Figure 22 illustrates this concept.

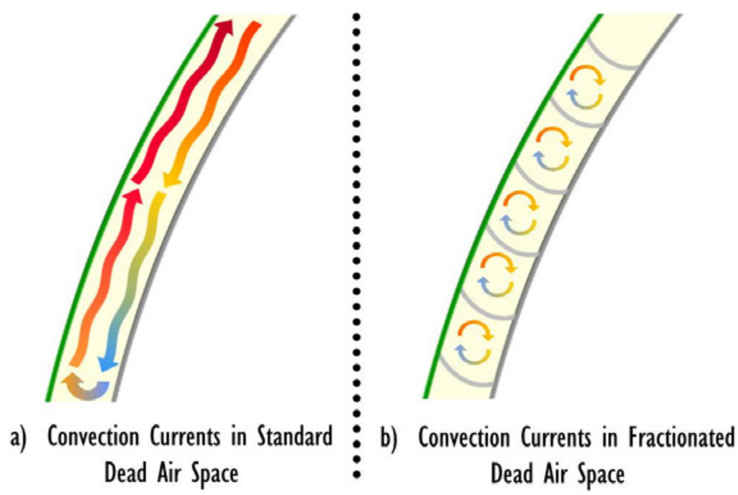

Figure 22. Convection Currents in Dead Air Space.

Creating a separate vented attic can complement this method. Currently, the TEMPER, MGPTS, Medical SSS and the MSS vent the airspace between the liner and the cladding. All four place the vent near the apex in order to release the hottest air. While in theory this may increase the shelter's thermal efficiency, it has never been conclusively proven with test data. Because the dead air space is used as insulation, allowing the air to move around decreases it's effectiveness. However, venting the hot air out of an attic does provide thermal benefit because it lowers the attic air temperature and thus slows the heat transfer rate from the top of the shelter to the shelter interior. This is a method found on most conventional houses. So a better configuration would be to separate the dead air space from the attic. This way, the benefit of venting hot air from the attic would be retained, and the insulative value of the dead air space would not be lost from air movement.

CONCLUSIONS

A TCPS gains thermal energy from radiation, primarily the sun, convection with the ambient environment, personnel and equipment inside the shelter, and controlled air exchange of ambient temperature air through the filter/blower unit. Thermal conduction through the ground is site and climate specific, and normally will reach an equilibrium point, for which its impact will be minimal. During cold weather, the shelter can lose more thermal energy through radiation than it gains and it also loses energy through thermal convection.

Minimizing radiant heat transfer and maintaining membrane separation is the key to creating a thermally efficient collectively protected shelter. Because materials used for soft-walled shelter construction typically have no insulative value, these two criteria will have the most significant impact upon thermal efficiency. For membrane separation, thermal energy has to move through an additional convective step in the dead air space to enter the shelter, as opposed to a single conductive step if the layers press against each other.

The techniques described in this paper all have different degrees of impact on TCPS thermal efficiency. The following is a summary of those techniques listed in order of their thermal impact on the TCPS from the greatest to the least impact.

1. Insure that CB liner does not make direct physical contact with the shelter liner or cladding.
2. The shelter cladding and liner should be configured to form a dead air space, and both the cladding and liner need to be as tight and leak proof as possible to prevent infiltration into the dead air space(s). The liner should be sealed to the floor, and should have as few hook and loop seams as possible.
3. A radiant barrier (material with high reflectivity and low emissivity) facing outward should be provided.
4. The dead air space can be subdivided horizontally to prevent vertical convective currents from forming.
5. A vented attic is separate from the dead air space.

Some of these recommendations have already been tested and showed very positive results. Testing has shown that a TCPS that does not maintain membrane separation could be unusable because of interior temperatures despite the use of a high capacity ECU. Testing has also proven the value of the dead air space and of sealing the liner. The significance of the radiant barrier is becoming accepted by the housing industry, and future testing is planned to show its contribution in deployable shelters. Subdividing the dead air space and having a separate vented attic will also be quantified by future testing. Figure 23 illustrates a theoretical shelter that implements each of these recommendations.

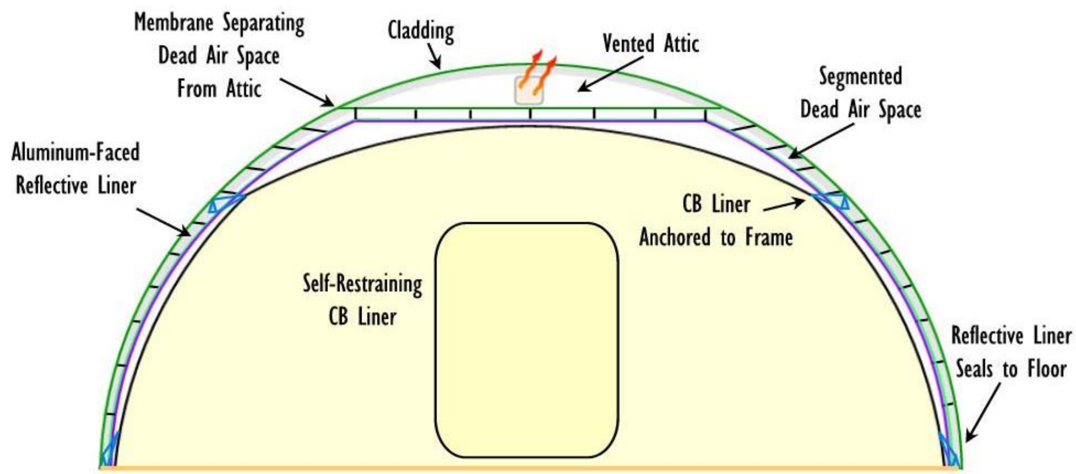

Figure 23. Cross Section of Thermally Efficient Shelter.

ACKNOWLEDGMENTS

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[i] *Collectively Protected Expeditionary Medical Support Shelter High Temperature Test Preliminary Results*, TEAS Reference Number 2001159-60U, published 13 December 2000.

[ii] *High Temperature Test Results for the Interim Collective Protection System (ICPS)*, TEAS Reference Number 2002285-60U, published 31 January 2002.

[iii] Dr. Gregor Harvie did he PhD thesis on the thermal effects inside tensioned fabric structures at the Welsh School of Architecture in Great Britain.

[iv] ASHRAE Fundamentals Handbook, page 26.9.

[v] The FFA-400 is a 400 cfm filter/blower unit. It is used to pressurize one shelter of 600 to 100 sqft floorplace.

[vi] FFA-400 and M28 blower/HSFC temperature rises are recorded in the *FFA-400 Test Report*, TEAS Reference Number 2002235-60U, published 18 January 2001.

[vii] Internal load estimates come from ASHRAE Fundamentals Handbook, Chapters 28 and 29.

[viii] Dr. Gregor Harvie, *The Thermal Behavior of Spaces Enclosed by Fabric Membranes.*

[ix] The 50 to 60% reduction is an approximate calculation based upon data from the Small Shelter climatic testing. Laboratory testing will be done to obtain actual results for the final version of this study, due to be published in March 2003.

[x] *High Temperature Test Results for Collectively Protected Expeditionary Medical Support Shelter*, TEAS Reference Number 2001164-60U, published 18 January 2001.

[xi] The Field Deployable Environmental Control Unit (NSN 4120-01-449-0459) is a 5-ton chem./bio hardened ECU with both cooling and heating capability.

[xii] R-Values for Some Common Building Materials, *Physics for Scientists and Engineers*, Fourth Edition, p. 571.